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-Technical Report-

Quadrotor for Increased Situational Awareness for Ground Vehicles

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14. ABSTRACT This project received TARDEC Innovation Project funding in January 2014 to explore the concept of employing a quadrotor to improve situational awareness for ground vehicles in urban environments. This report details the modeling & simulation effort and the indoor flying quadrotor effort.					
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1.0 INTRODUCTION AND OBJECTIVES

This project received TARDEC Innovation Project funding in January 2014 to explore a concept. The concept was to determine if a quadrotor could improve situational awareness for ground vehicles in urban environments. The vehicle commander must maintain situational awareness near the vehicle, and this may not be met by existing systems. Such systems include mast-mounted EO/IR, which can be limited by height, and UAS, which may not be available to the vehicle commander. Some ideas to investigate included what camera resolutions would be useful, where these cameras should be positioned, and whether a tethered quadrotor was feasible. Work concluded in October 2014.

1.1 IDENTIFICATION OF ISSUES AND APPROACH

The team began with brainstorming of the various technical issues to be solved in such a system. Figure 1 provides a summary of the major technical issues to be overcome. The team focused on three areas with limited scope.

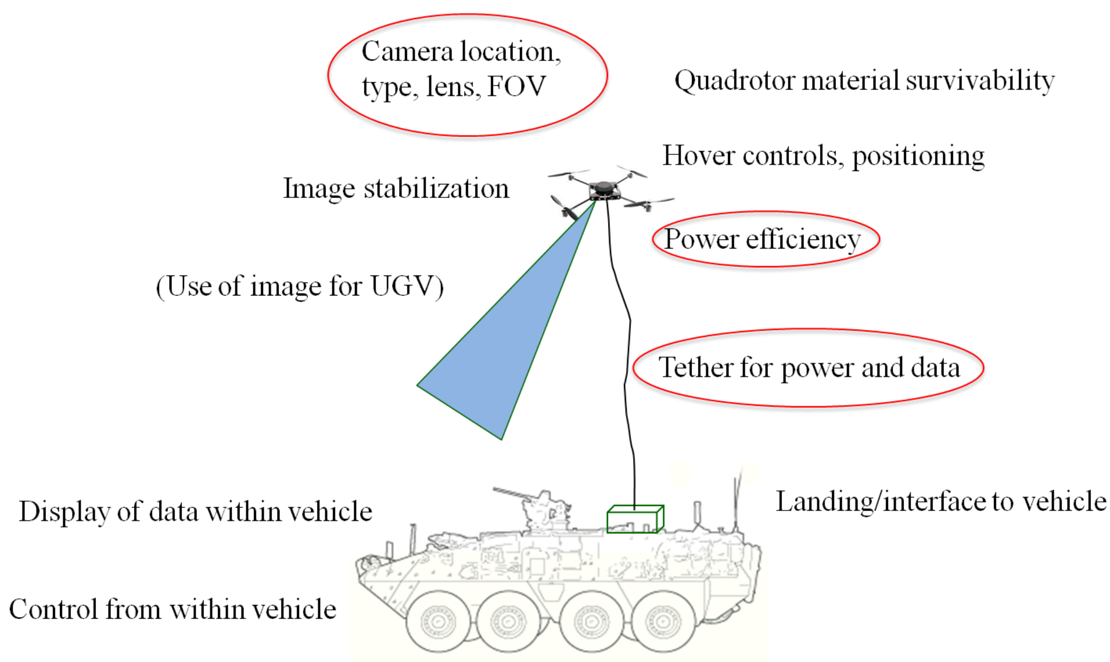

Figure 1. Technical issues for integration of quadrotor with vehicle.

Part of the effort was in modeling and simulation of camera location, type, lens, and field of view (FOV). With modification of the 360SA Visualization tool, the coverage of various configurations of cameras could be determined in a simulated urban environment.

The quadrotor flying part of the project was carried out by indoor flights. A temporary net structure and operating procedures provided an adequate risk reduction for these indoor flights. The flights focused on getting tether power for operation, and studying the efficiency of such a system.

2.0 MODELING AND SIMULATION

The surveillance performance of the system is affected by 3 key parameters: sensor resolution, FOV (lens zoom), and altitude. To measure this, we placed eight mannequins in a simulated urban environment using our in-house 360SA Visualization tool. To exhibit different effects we placed the mannequins in the following situations: on a 2nd story balcony; on a 3rd story roof partially obscured by parapets; in a courtyard behind a wall by a tree; on a sidewalk under an awning; in a courtyard behind a two story building, and three in plain view at 50m, 100m, and 200m.

We then selected various commercially available cameras and lenses. In all we measured all permutations of 3 standard camera bodies, 3 or 4 common lenses per camera, at six different altitudes. With each configuration we measured the number of camera pixels that "saw" each target (the "actual" count) as well as the number of pixels that could have seen the target had the view not been obstructed by buildings, trees, etc. (the "potential" count).

From the pixel totals we can calculate various measure of performance. The quantity of actual pixel hits is a measure the overall performance of the system detecting targets. The quantity of potential hits isolates the performance of the camera system due to range. The ratio of actual pixel hits to potential pixel hits isolates the situational performance of the system due to positioning.

Figure 2 shows a measurement from the tool. The intensity (whiteness) of a pixel increases with distance. The mannequin on the balcony has been colored red to highlight the actual pixels seen with bright red and the obstructed pixels with a darker red. The red pixels combined are the potential total.

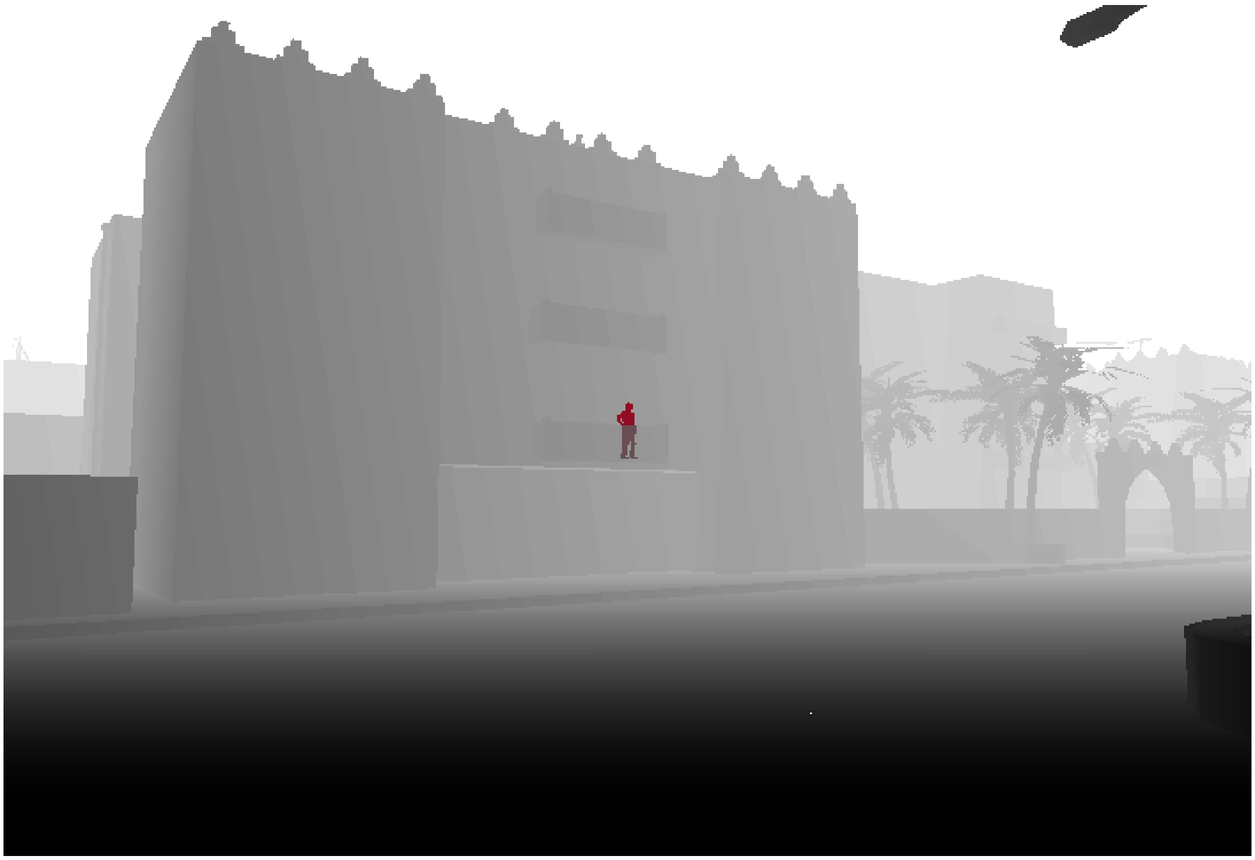

Figure 2. A measurement from the 360SA Visualization tool with target highlighted.

Looking at the resulting data in Appendix A we can see that the data properly exhibit basic properties of cameras. As a camera moves farther from a target the number of pixel hits decreases. Higher resolution cameras have more pixel hits on a given target. Wider angle lenses have fewer pixels on any one target as they view a larger area. Finally, from a given position, every configuration has the same ratio of potential to actual pixel hits on a given target (within rounding error) as this is a measurement of how obscured the target is.

Furthermore we can draw the following conclusions from the data. Increased resolution is always better – more pixels provide more detail. While the data shows that narrow lenses are better, this comes at the expense of situational awareness. Depending on the situation, particularly maximum range and size of targets of interest, there may not be one correct lens for the job. Until higher resolution sensor technology comes to market, an adjustable lens may be required.

One key takeaway regarding altitude is that there is no perfect altitude for the quadrotor. The target in the front courtyard exhibits this best. If the quadrotor is too low then it can't see the target over the wall. If it flies too high then the target becomes obscured by a tree. Flying higher allows better vision behind the building but as the quadrotor flies higher the distance to the target increases thus making it harder to detect.

3.0 QUADROTOR TEST FLIGHTS

3.1 TEST PLATFORMS AND MODIFICATIONS

The flight testing used a commercial-off-the-shelf quadrotor, the 3D Robotics Quadrotor with Pixhawk autopilot, as shown in Figure 3.

Figure 3. Tethered quadrotor unpowered, on the floor within netted flying area.

The quadrotor (#3) was modified for tethered operation, as shown in Figure 4. The typical operating voltage of the quadrotor using a Lithium Polymer (LiPo) battery is 14.8V DC. This was replaced with a 48V to 15 V converter module, the Vicor V48A15C500BL. This was chosen for its size, reliability, and ability to provide 500W of power. Because the converter module was meant for board mounting, two printed circuit boards were fabricated to allow connection of the power converter to the tether and quadrotor battery connection, respectively. The converter module has a baseplate for thermal sink, which is on the bottom of the power converter. As it is mounted upside down, the baseplate is mounted about 1 inch from the bottom of the quadrotor, allowing airflow for heat dissipation.

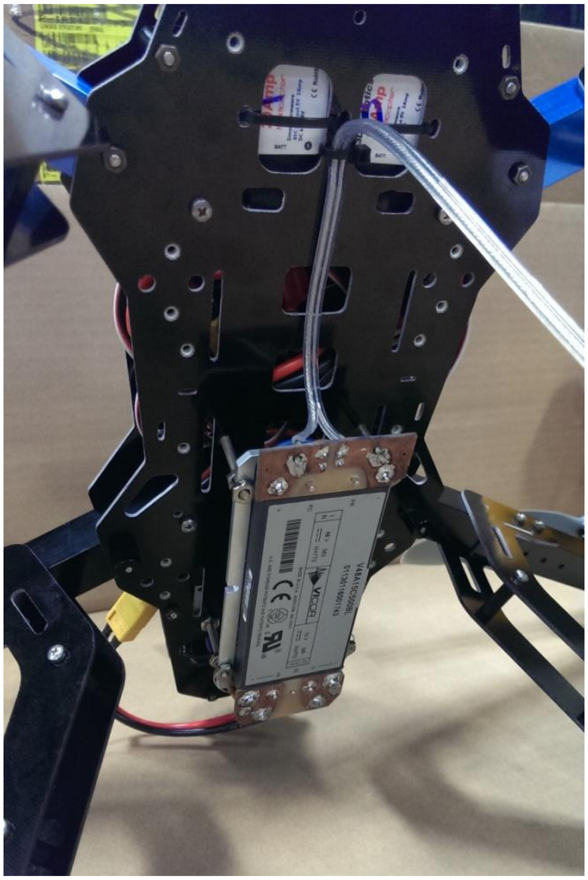

Figure 4. DC/DC converter mounted on bottom of quadrotor.

The quadrotor includes a power module that monitors voltage and current, and records these values at 1 Hz on the Pixhawk autopilot's micro-SD card. These logs provide a means to determine the total power used by the quadrotor, with 1 second resolution.

The base requires an AC-DC Converter that provides 48V DC at 500 W. The chosen power supply was a TDK-Lambda GWS50048. The voltage and current output of this power supply were monitored using a shunt.

The tether was 20 AWG, 2 wire, high voltage continuous flex flat cable. The insulation material was silicone rubber, allowing temperatures to 500F.

3.2 TEST PROCEDURE AND RESULTS

All operations of the quadrotor were conducted within the guideline of the SOP established for the TARDEC Indoor Quadrotor Laboratory. A separate risk management worksheet was completed and signed, outlining control measures for identified hazards. The flights were conducted within a net suspended from the ceiling in the Ground Vehicle Robotics (GVR) high bay, with an approximate 12 foot cube of flying space, as in Figure 5. The net also covered the top of the cube. Although the quadrotor is capable of GPS flight, all flights were conducted indoors, without GPS lock. The quadrotor was then restricted to operation in stabilized or altitude hold modes. Most flights were radio controlled, in stabilized mode, requiring the near constant attention of the pilot.

A test was first performed with the original configuration quadrotor (#1) with a LiPo battery. These were relatively large 4000mAh 4S 35C batteries. From a starting voltage of 16.81V, the quadrotor flew for 11 minutes, 59 seconds to a final voltage of 14.47V. This quadrotor weighed 1374 grams, not including the battery weight of 417 grams.

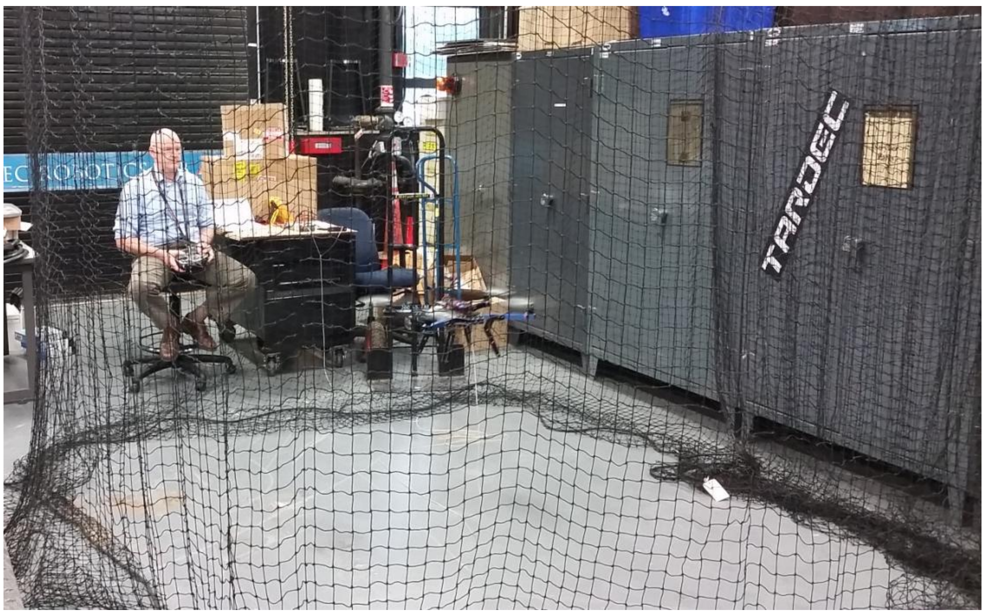

Figure 5. Tethered quadrotor in flight within netted flying area. Pilot at left.

A test was conducted to establish the operating characteristics of the tethered quadrotor (#3). First, the incremental power measurements were made with the tethered quadrotor on the ground, with results shown in Table 1. One value of note is the $P=I^2R$ value of power lost in the tether; even at 0.5 ohms of resistance in 20 feet of tether, the power lost at higher amperage is significant. It is at these higher amperage values that the DC/DC converter on the quadrotor becomes more efficient.

Table 1. Power values for tethered quadrotor on ground.

	Power Supply			Tether, 20 ft.	Quadrotor			Dissipated by DC/DC	Efficiency of DC/DC	Fraction to Quad
throttle setting	(V)	(A)	(W)	(W)	(V)	(A)	(W)	(W)	%	%
zero	47.92	0.39	18.7	0.1	14.95	0.07	1.0	17.6	5.6	5.6
prop spin	47.92	1.31	62.8	0.9	14.9	2.69	40.1	21.8	64.7	63.8
low (on ground)	47.92	2.17	104.0	2.4	14.9	4.75	70.8	30.9	69.6	68.1
high (on ground)	47.92	7.63	365.6	29.1	14.69	17.98	264.1	72.4	78.5	72.2
max (on ground)	47.92	9.27	444.2	43.0	14.65	21.68	317.6	83.6	79.2	71.5

A test was conducted with a LiPo battery, and for a total quadrotor weight of 1.839 kg, it required 286 W in hover; which is 155 W/kg.

A test was conducted to determine the max thrust possible by the tethered quadrotor, this was performed by the configuration shown in Figure 6. A 2.26 kg weight was placed on the digital scale below the quadrotor, with a nearly taut lifting line. Max thrust was applied, but limited by the overcurrent protection of the AC-DC converter, at 11.1 Amps. For this test, the quadrotor lifted an additional 0.84 kg. It is possible that the quadrotor with conventional LiPo batteries could exceed this value.

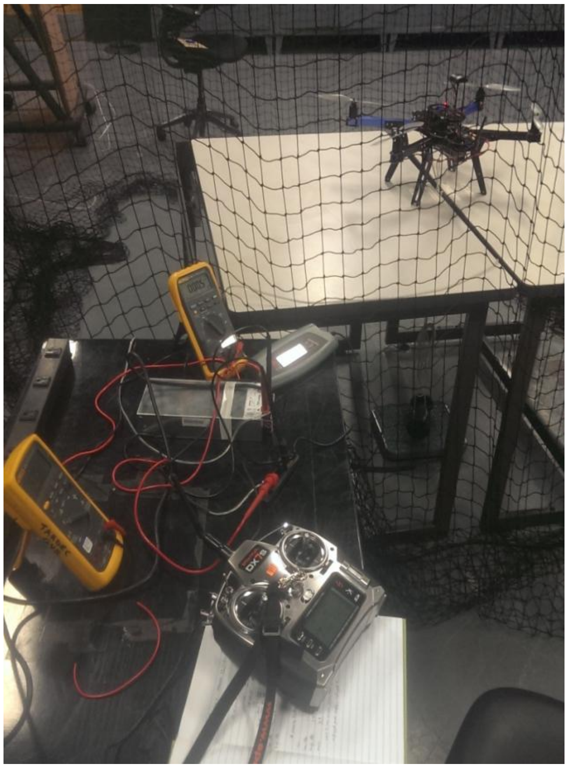

Figure 6. Max thrust test setup for quadrotor, measuring AC-DC voltage, current, and the lifted weight value.

4.0 CONCLUSIONS

1. The safe voltage of 50V has excessive power losses in the tether for extended lengths. To avoid wasting this power, a higher DC transmission voltage should be chosen.

2. The tethered quadrotor can provide longer flight times than conventional LiPo battery powered quadrotors. There is a limit to the current provided at the ground, which can limit lifting power of the quadrotor.

3. When selecting a camera, higher resolution is always better. When selecting a lens, wider provides more situational awareness but narrow provides more detail on a target. With the resolutions available on currently available cameras a zoom lens is the only means to have it both ways.

4. There is no optimal altitude for the quadrotor. The height must be controllable to adjust for various situations. However, as performance decreases with range the quadrotor should be flown "high enough, but no higher".

APPENDIX A

Camera	Height	HRes	VRes	HFOV	VFOV	Balcony Actual	Balcony Potential	Courtyard Actual	Courtyard Potential	Roof Actual	Roof Potential	Overhang Actual
ATSC Narrow	0	704	480	65.47	51.48	80	213	0	64	25	148	120
ATSC Narrow	10	704	480	65.47	51.48	119	190	61	61	124	184	90
ATSC Narrow	20	704	480	65.47	51.48	89	122	30	49	121	142	0
ATSC Narrow	30	704	480	65.47	51.48	79	88	2	43	130	131	5
ATSC Narrow	40	704	480	65.47	51.48	44	51	1	28	74	75	0
ATSC Narrow	50	704	480	65.47	51.48	21	31	13	23	48	52	0
ATSC Medium	0	704	480	81.2	65.47	49	119	0	33	14	88	70
ATSC Medium	10	704	480	81.2	65.47	67	111	32	32	71	106	45
ATSC Medium	20	704	480	81.2	65.47	64	82	25	25	90	99	12
ATSC Medium	30	704	480	81.2	65.47	40	43	1	21	71	73	3
ATSC Medium	40	704	480	81.2	65.47	26	28	0	17	43	43	0
ATSC Medium	50	704	480	81.2	65.47	14	20	8	13	25	27	0
ATSC Wide	0	704	480	104.25	87.92	17	44	0	15	6	35	29
ATSC Wide	10	704	480	104.25	87.92	28	43	15	15	29	42	23
ATSC Wide	20	704	480	104.25	87.92	25	32	14	14	38	41	7
ATSC Wide	30	704	480	104.25	87.92	17	20	0	11	29	29	2
ATSC Wide	40	704	480	104.25	87.92	9	11	0	10	19	19	0
ATSC Wide	50	704	480	104.25	87.92	4	8	4	6	8	11	0
1080p Narrow	0	1920	1080	65.47	39.76	672	1671	0	510	206	1237	958
1080p Narrow	10	1920	1080	65.47	39.76	972	1566	437	485	997	1515	710
1080p Narrow	20	1920	1080	65.47	39.76	879	1125	364	415	1288	1415	212
1080p Narrow	30	1920	1080	65.47	39.76	649	696	23	322	1035	1041	41
1080p Narrow	40	1920	1080	65.47	39.76	424	436	1	252	658	668	0
1080p Narrow	50	1920	1080	65.47	39.76	220	286	126	192	414	427	0
1080p Medium	0	1920	1080	81.2	51.48	321	753	0	271	154	567	148
1080p Medium	10	1920	1080	81.2	51.48	543	877	251	273	553	846	409
1080p Medium	20	1920	1080	81.2	51.48	489	625	210	231	732	801	121
1080p Medium	30	1920	1080	81.2	51.48	371	401	10	180	571	576	22
1080p Medium	40	1920	1080	81.2	51.48	236	246	0	140	373	378	0
1080p Medium	50	1920	1080	81.2	51.48	144	159	51	110	222	228	0

Camera	Height	Overhang Potential	Behind Actual	Behind Potential	WalkNear Actual	WalkNear Potential	WalkMid Actual	WalkMid Potential	WalkFar Actual	WalkFar Potential
ATSC Narrow	0	120	0	81	55	55	18	18	0	0
ATSC Narrow	10	110	0	76	51	51	18	18	0	0
ATSC Narrow	20	95	2	75	43	43	16	16	0	0
ATSC Narrow	30	60	48	49	31	32	12	12	0	0
ATSC Narrow	40	40	36	38	26	26	14	14	0	0
ATSC Narrow	50	26	23	23	19	19	12	12	0	0
ATSC Medium	0	71	0	50	29	29	5	5	0	0
ATSC Medium	10	57	0	45	28	28	6	6	0	0
ATSC Medium	20	45	0	36	26	26	5	5	0	0
ATSC Medium	30	31	25	26	22	22	4	4	0	0
ATSC Medium	40	22	18	18	18	18	5	5	0	0
ATSC Medium	50	15	14	15	12	13	2	3	0	0
ATSC Wide	0	29	0	18	17	17	0	0	0	0
ATSC Wide	10	28	0	21	16	16	0	0	0	0
ATSC Wide	20	20	0	16	16	16	0	0	0	0
ATSC Wide	30	14	13	13	10	10	0	0	0	0
ATSC Wide	40	10	10	10	6	6	0	0	0	0
ATSC Wide	50	8	6	7	4	6	0	0	0	0
1080p Narrow	0	958	0	686	438	438	101	101	26	26
1080p Narrow	10	864	0	631	418	418	100	100	26	26
1080p Narrow	20	666	0	517	355	355	96	96	26	26
1080p Narrow	30	483	391	392	278	278	90	90	26	26
1080p Narrow	40	334	282	285	205	205	85	85	26	26
1080p Narrow	50	239	203	209	155	158	77	77	25	25
1080p Medium	0	627	0	477	273	273	57	57	16	16
1080p Medium	10	496	0	351	232	232	54	54	16	16
1080p Medium	20	377	0	288	197	197	54	54	16	16
1080p Medium	30	271	219	221	158	158	50	50	16	16
1080p Medium	40	192	157	158	116	116	42	42	17	17
1080p Medium	50	134	119	120	86	88	39	39	17	17

Camera	Height	HRes	VRes	HFOV	VFOV	Balcony Actual	Balcony Potential	Courtyard Actual	Courtyard Potential	Roof Actual	Roof Potential	Overhang Actual
1080p Wide	0	1920	1080	104.25	71.75	170	420	0	129	49	305	253
1080p Wide	10	1920	1080	104.25	71.75	241	390	120	122	251	386	176
1080p Wide	20	1920	1080	104.25	71.75	216	273	99	105	322	353	53
1080p Wide	30	1920	1080	104.25	71.75	161	176	7	82	259	262	10
1080p Wide	40	1920	1080	104.25	71.75	105	112	0	65	153	158	0
1080p Wide	50	1920	1080	104.25	71.75	49	71	33	49	100	108	0
BlackFly f3.3	0	2592	1944	81.65	65.89	679	1691	0	517	206	1245	969
BlackFly f3.3	10	2592	1944	81.65	65.89	980	1582	441	490	1008	1530	717
BlackFly f3.3	20	2592	1944	81.65	65.89	891	1142	370	420	1290	1418	216
BlackFly f3.3	30	2592	1944	81.65	65.89	657	707	21	326	1041	1048	40
BlackFly f3.3	40	2592	1944	81.65	65.89	425	437	1	255	660	670	0
BlackFly f3.3	50	2592	1944	81.65	65.89	221	287	128	194	418	432	0
BlackFly f5.0	0	2592	1944	59.39	46.31	1566	3877	0	1190	465	2858	2250
BlackFly f5.0	10	2592	1944	59.39	46.31	2268	3631	983	1117	2305	3509	1665
BlackFly f5.0	20	2592	1944	59.39	46.31	2034	2588	826	946	2985	3282	500
BlackFly f5.0	30	2592	1944	59.39	46.31	1313	1496	1	739	2036	2073	0
BlackFly f5.0	40	2592	1944	59.39	46.31	981	1003	1	582	1523	1536	0
BlackFly f5.0	50	2592	1944	59.39	46.31	514	651	293	442	968	982	0
BlackFly f9.0	0	2592	1944	35.16	26.73	5085	12567	0	3835	1517	9274	7288
BlackFly f9.0	10	2592	1944	35.16	26.73	7319	11755	3106	3609	7450	11348	5390
BlackFly f9.0	20	2592	1944	35.16	26.73	5317	7088	978	2893	7415	8442	0
BlackFly f9.0	30	2592	1944	35.16	26.73	4930	5287	178	2473	7677	7746	306
BlackFly f9.0	40	2592	1944	35.16	26.73	3033	3163	18	1886	4556	4585	0
BlackFly f9.0	50	2592	1944	35.16	26.73	1690	2106	964	1448	3156	3184	0
BlackFly f12.0	0	2592	1944	26.73	20.21	9038	22328	0	6819	2694	16449	12960
BlackFly f12.0	10	2592	1944	26.73	20.21	13013	20914	5488	6428	13273	20223	9607
BlackFly f12.0	20	2592	1944	26.73	20.21	11700	14904	4662	5486	17193	18894	2876
BlackFly f12.0	30	2592	1944	26.73	20.21	8738	9370	309	4390	13678	13787	543
BlackFly f12.0	40	2592	1944	26.73	20.21	5779	5815	5	3386	8858	8923	0
BlackFly f12.0	50	2592	1944	26.73	20.21	3026	3747	1717	2562	5644	5671	0

Camera	Height	Overhang Potential	Behind Actual	Behind Potential	WalkNear Actual	WalkNear Potential	WalkMid Actual	WalkMid Potential	WalkFar Actual	WalkFar Potential
1080p Wide	0	253	0	163	110	110	25	25	1	1
1080p Wide	10	217	0	157	107	107	26	26	1	1
1080p Wide	20	169	0	133	93	93	26	26	1	1
1080p Wide	30	124	100	101	72	72	26	26	1	1
1080p Wide	40	86	73	74	51	52	22	22	1	1
1080p Wide	50	61	51	52	35	36	23	23	1	1
BlackFly f3.3	0	969	0	689	442	442	102	102	25	25
BlackFly f3.3	10	874	0	636	422	422	101	101	26	26
BlackFly f3.3	20	674	0	517	356	356	97	97	26	26
BlackFly f3.3	30	487	394	395	283	283	96	96	26	26
BlackFly f3.3	40	336	282	286	206	206	85	85	26	26
BlackFly f3.3	50	240	207	210	156	158	77	77	25	25
BlackFly f5.0	0	2250	0	1586	1024	1024	232	232	52	52
BlackFly f5.0	10	2026	0	1463	965	965	231	231	53	53
BlackFly f5.0	20	1566	0	1191	826	826	224	224	52	52
BlackFly f5.0	30	1177	999	1008	687	688	215	215	54	54
BlackFly f5.0	40	771	656	665	493	493	192	192	51	51
BlackFly f5.0	50	540	475	481	365	365	174	174	49	49
BlackFly f9.0	0	7288	0	5126	3323	3323	737	737	175	175
BlackFly f9.0	10	6565	0	4746	3165	3166	742	742	174	174
BlackFly f9.0	20	5333	0	4459	2775	2775	732	732	180	180
BlackFly f9.0	30	3630	2925	2932	2100	2100	673	673	174	174
BlackFly f9.0	40	2586	2294	2316	1660	1661	641	641	176	176
BlackFly f9.0	50	1772	1545	1555	1170	1170	564	564	170	170
BlackFly f12.0	0	12960	0	9108	5875	5875	1318	1318	305	305
BlackFly f12.0	10	11690	0	8432	5614	5614	1319	1319	315	315
BlackFly f12.0	20	9045	0	6882	4758	4758	1274	1274	312	312
BlackFly f12.0	30	6452	5187	5203	3736	3736	1199	1199	306	306
BlackFly f12.0	40	4483	3779	3816	2795	2796	1102	1102	302	302
BlackFly f12.0	50	3141	2757	2778	2092	2094	1006	1006	298	298